Anomalous Single Production of the Fourth SM Family Quarks and Leptons at Future Electron-Positron Colliders

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Abstract

We study the possibility to produce single fourth SM family fermions at electron-positron colliders via anomalous $\gamma - f_4 - f$ interactions.

I. Introduction

Flavor Democracy [1-4] forces [5-7] the existence of the fourth fermion family in the Standard Model (SM). In this case, the smallness of the first three neutrino masses gains a natural explanation [8] without see-saw mechanism. In addition these small masses are compatible with large mixing angles, assuming that neutrinos are of the Dirac type [9]. The latest precision electroweak data allows the existence of the extra SM families [10,11]. Moreover, as quoted from [11] "quality of the fit for the one new generation is as good as for zero new generations (Standard Model)". Current experimental lower limits on the fourth SM family fermions masses are: 92.4 GeV for l_4, 45.0 (83.3) GeV for stable (unstable) Dirac ν_4, 199 (128) GeV for d_4 decaying via neutral-current (charged-current) channel [12].

The fourth family quarks will be copiously produced at the LHC [12,13]. These quarks lead to an assential enhancement of the Higgs boson production via gluon-gluon fusion at the Tevatron and LHC and, as a consequence, the "golden mode" (H$\longrightarrow ZZ \longrightarrow$ 4l) becomes important even at the upgraded Tevatron [14,15]. On the other hand, future lepton colliders will be advantageous for investigation of the fourth SM family leptons and quarkonia [16,17].

Main parameters of proposed $\mathrm{e}^+\mathrm{e}^-$ colliders are given in the Table 1. As can be seen, the first stage will cover 500 GeV center-of-mass energy. On the other hand, expected masses of the fourth SM family fermions are close to each other and lie between 300 and 700 GeV (see [7] and references therein). For this reason their pair production at the first stage linear colliders is not promising. Therefore, in this case we must look for the single production via anomalous

interactions. Arguments presented in [18] concerning t-quarks anomalous interactions are already valid for fourth family fermions.

In this paper we study single production of the fourth family leptons and quarks at e^+e^- colliders. For the time being we restrict ourselves to the anomalous interactions mediated by photon.

II. Anomalous $\gamma - f_4 - f$ interactions

Within the Standard Model there are no anomalous vertices like $\gamma - f_4 - f$ at the tree level, they arise only due to loop contributions and, therefore, are suppressed. On the other hand, these vertices are essentially enhanced in various extensions of the SM. For example, the possibility of anomalous transitions exist in a wide class of dynamical models for the fermion mass generation [18]. Following [19,20], the $\gamma - f_4 - f$ vertices can be written as

$$\Gamma_\mu^\gamma = \mathrm{k}_\gamma \frac{\mathrm{ee}_f}{\Lambda} \sigma_{\mu\nu} \left(\mathrm{g}_1 \mathrm{P}_l + \mathrm{g}_2 \mathrm{P}_\mathrm{r} \right) \mathrm{q}^\nu \tag{1}$$

where Λ is the new physics cutoff, $e = \sqrt{4\pi\alpha}$, e_f =-1, 2/3 and -1/3 for l_4, u_4 and d_4, respectively, k_γ is the strength of the anomalous coupling, $\sigma^{\mu\nu} = (\gamma^\mu \gamma^\nu - \gamma^\nu \gamma^\mu)/2$, $\mathrm{P}_l = (1+\gamma_5)/2$, $\mathrm{P}_r = (1-\gamma_5)/2$, $\mathrm{g}_1$and g_2 denote the relative magnitude of the left and right components of the $f_4 - f$ current, $g_1^2 + g_2^2 = 1$. Parametrization used in [18] is obtained from (1) by replacing.

$$\frac{C_\gamma}{m_t} = \mathrm{k}_\gamma \frac{\mathrm{ee}_f}{\Lambda} \frac{g_1 + g_2}{2}, \quad \frac{D_\gamma}{m_t} = \mathrm{k}_\gamma \frac{\mathrm{ee}_f}{\Lambda} \frac{g_1 - g_2}{2}$$

III. Decays of the fourth family fermions

Decay width for the SM modes is given by,

$$\Gamma\left(f_4 \longrightarrow f' W\right) = \frac{G_F}{8\pi\sqrt{2}} \left|V_{4i}\right|^2 M^3 \sqrt{1 - \frac{(m_W + m_f)^2}{M^2}} \sqrt{1 - \frac{(m_W - m_f)^2}{M^2}}$$

$$\left[1 + \frac{(m_W + m_f)^2}{M^2} + \frac{m_W m_f}{M^2} - 2\frac{(m_W^2 - m_f^2)^2}{M^4} \right] \tag{2}$$

where V_{4i} is the corresponding element of the 4x4 CKM matrix, M denotes the mass of the fourth family fermion. Anomalous interactions lead to additional FCNC decay modes. Let us remind that, at this stage we constrain ourselves with anomalous interactions mediated by photon only. According to (1) we obtain:

$$\Gamma\left(f_4 \longrightarrow f\gamma\right) = \mathrm{k}_\gamma^2 \frac{\alpha \mathrm{e}_f^2}{4} \frac{M^3}{\Lambda^2} (1 - \frac{m_f^2}{M^2}) \left(1 + \frac{m_f^2}{M^2} - 2\frac{m_f^4}{M^4} \right) \tag{3}$$

As seen from (2) SM decay modes are determined by CKM matrix elements. Within the parametrization given in [6-8] the main SM decay modes are $u_4 \longrightarrow bW^+$, $d_4 \longrightarrow tW^-$, $l_4 \longrightarrow \nu_\tau W^-$, $\nu_4 \longrightarrow \tau W^+$ and corresponding CKM matrix elements are $|V_{u_4 b}| \simeq |V_{d_4 t}| \simeq 0.005$, $|V_{l_4 \nu_\tau}| \simeq |V_{\nu_4 \tau}| \simeq 10^{-4}$, respectively.

Differing from the case of t-quark decays [19], where SM decay mode is dominant with respect to decay modes mediated by anomalous interaction, in decays of fourth family fermions anomalous interaction mode may be well dominating. Neglecting masses of W-boson and first three family fermions compared to fourth family fermion masses, which are taken to be equal to 400 GeV for numerical estimations, and assuming the cutoff scale Λ to be equal to m_4 we get from (2) and (3) following rough values of k_γ^2 which indicates dominance of anomalous mode: $|k_\gamma|^2 > 2.5\times10^{-7}$ for l_4, $|k_\gamma|^2 > 1.4\times10^{-3}$ for u_4 and $|k_\gamma|^2 > 5.6\times10^{-3}$ for d_4.

IV. Total cross section for single production of fourth family fermions

Using Eq. (1) for anomalous $\gamma - f_4 - f$ vertex one can easily obtain the cross section for the process $e^+e^- \to \gamma^* \to f_4\overline{f}$,

$$\sigma = \frac{N_c}{3}\frac{\pi\alpha^2}{s}k_\gamma^2\frac{M^2}{\Lambda^2}e_f^2\frac{s}{M^2}\sqrt{1-\frac{(M+m_f)^2}{s}}\sqrt{1-\frac{(M-m_f)^2}{s}}$$

$$\left[1+\frac{(M+m_f)^2}{s}+\frac{Mm_f}{s}-2\frac{(M^2-m_f^2)^2}{s^2}\right] \tag{4}$$

Cross section values as a function of the fourth family fermions mass for $\sqrt{s} = 500$ GeV are presented in the Fig. I. Taking 25 events per working year (10^7 s) as the observation limit, we see that $\sqrt{s} = 500$ GeV e^+e^- colliders with integrated luminosity of 100 fb^{-1}can reach the following upper limits for $|k_\gamma|^2$: 3.6×10^{-3} for $\overline{u}_4 u(c)$, 1.66×10^{-2} for $\overline{d}_4 d(s)$ and 5.4×10^{-3} for $\overline{l}_4 e(\mu,\tau)$. With M = 400 GeV the process $e^+e^- \to \gamma^* \to \overline{u}_4 t$ is kinematically forbidden at $\sqrt{s} =$ 500 GeV.

V. Conclusion

Although the first stage (500 GeV c.m. energy) of future lineer electron-positron colliders is not promising for the pair production of the fourth SM family fermions, it will yield important results for the single production via anomalous interaction. As an example, we show that sensitivity up to 0.01 can be reached for $|k_\gamma|^2$.

We studied single production via anomalous interaction with photon only. The production via Z is possible as well. In this case both k_γ and k_Z must be taken into account together. The corresponding analysis is being studied and will be reported in the next work.

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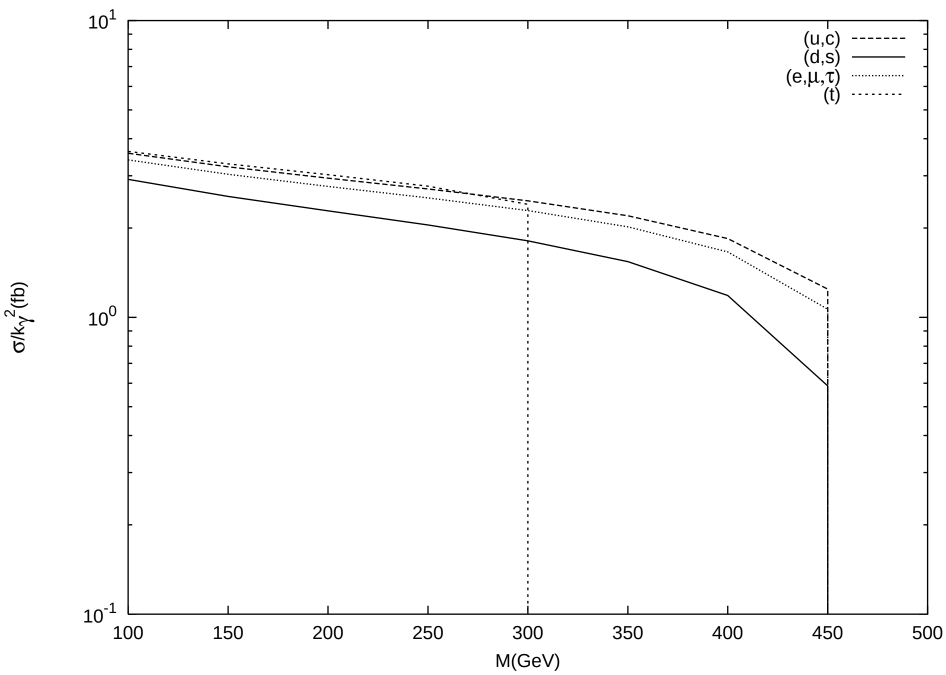
Table 1. Parameters of e^+e^- colliders.

	TESLA		JLC/	NLC	CLIC		
	1	2	1	2	1	2	3
$\sqrt{s}$, GeV	500	800	500	1000	500	1000	3000
L, 10^{34} cm^{-2}s^{-1}	3	5	2.5	2.5	1.4	2.7	10.0

Figure 1: The cross section as a function of M. Dashed, dotted, dashed-dotted and solid curves are correspond to $\overline{u}_4 u(c)$, $\overline{u}_4 t$, $\overline{l}_4 e(\mu, \tau)$ and $\overline{d}_4 d(s, b)$, respectively. Cross section is in fb, while M is in GeV.



(u,c)
(d,s)
(e,μ,τ)
(t)
10^1
10^0
10^{-1}
100
150
200
250
300
350
400
450
500
M(GeV)
σ/k_γ^2(fb)